Thermo-mechanical performance of Cu and SiO₂ filled coaxial through-silicon-via (TSV)

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Abstract: Analytical model for thermal stress in silicon induced by coaxial Through-silicon-via (TSV) is proposed. ANSYS is employed to verify the proposed model. It is shown that the average errors are ~2.5% for Cu and SiO₂ filled coaxial TSV. Based on the analytical model, thermo-mechanical performance of coaxial TSV is studied. Design guide lines for coaxial TSV are also given: 1) the smaller the sizes of metal parts, especially the outer metal shell, the better the thermo-mechanical performance; and 2) the dielectric size and the TSV height play unimportant roles on the thermal stress state.

Keywords: coaxial through-silicon-via (TSV), thermal stress, thermo-mechanical performance

Classification: Integrated circuits

References

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1 Introduction

Three-dimensional (3D) integrated circuits (ICs) have been widely acknowledged as an effective solution to the challenges of greater performance, smaller form factor and lower power consumption. Through-silicon-via (TSV) is the key component that provides a vertical physical and electrical connectivity with greatly reduced interconnection length among the stacked dies [1]. There are four main types of TSV profiles existing in the industry, namely, cylindrical, tapered, annular, and coaxial TSVs, respectively, depending on the etching processes applied to form the TSV. However, during the final annealing step, thermal stress will

be induced in silicon [2] due to the coefficient of thermal expansion (CTE) mismatch between TSV and silicon. The stress would affect the performance and reliability of transistors. The thermal stress induced by cylindrical and annular TSVs have been analyzed in detail [2, 3], while the thermo-mechanical performance of coaxial TSV has never been studied.

To facilitate capture of the thermo-mechanical characteristic of coaxial TSV, analytical model for the stress induced by coaxial TSV is proposed, and verified by employing ANSYS software. Based on the analytical model, this paper explores the thermo-mechanical performance of the Cu and SiO₂ filled coaxial TSV. Finally, section 5 concludes this paper, and gives design guide lines of coaxial TSV.

2 Analytical model

The baseline structure of coaxial TSV is shown in Fig. 1, where, M1, D, M2, and Si represent the cylindrical TSV metal (Cu), dielectric (SiO₂), tubular TSV metal, and silicon wafer, respectively. Table I lists the size parameters according to the current 3D TSV technology [4].

Fig. 1. Coaxial TSV in cylindrical coordinate

Table I. Design parameters of coaxial TSV

Parameter	Symbol	Value (μm)
TSV height	h	50
Cylindrical metal diameter	R_M	5
Dielectric thickness	t_D	3
Tubular metal thickness	t_M	2
Silicon wafer radius	R_{Si}	110

In accord with our previous work [3], quasi-3D Kane-Mindlin theory is used for the analytical model of thermal stress in Si induced by coaxial TSV, and only surface in-plane stress is studied, since active devices are generally manufactured in the surface of Si. The analytical stress model of coaxial TSV is simply given as following. Please refer to [3] for more details about the quasi-3D Kane-Mindlin theory.

The normal stress along the radial direction can be described as

$$\sigma_{rr}^P = 2\mu_P \frac{3\lambda_P + 2\mu_P}{\lambda_P + 2\mu_P} a_P - 2\mu_P \frac{b_P}{r^2} - 2\mu_P I_1(\sqrt{A_P r}) \frac{c_P}{r} + 2\mu_P K_1(\sqrt{A_P r}) \frac{d_P}{r} \quad (1)$$

where P represents different materials; the shear modulus $\mu_P = E_P / [2(1 + \nu_P)]$; $\lambda_P = 2\mu_P \nu_P (1 - 2\nu_P)^{-1}$; $A_P = 12(\mu_P + \lambda_P) (2\mu_P + \lambda_P)^{-1} h^{-2}$; $h = 0.5D$; D is wafer thickness; I_l and K_l are the l th-order modified Bessel functions of the first kind and the second kind, respectively; and a_P , b_P , c_P , and d_P are constants, determined from the boundary conditions, which are different from the previous work [3], for the continuity of the displacements and stresses at interfaces as follows

$$\begin{aligned} u_r^{P_i}(R_i) &= u_r^{P_{i+1}}(R_i), u_z^{P_i}(R_i) = u_z^{P_{i+1}}(R_i), \\ \sigma_{rr}^{P_i}(R_i) &= \sigma_{rr}^{P_{i+1}}(R_i), \sigma_{rz}^{P_i}(R_i) = \sigma_{rz}^{P_{i+1}}(R_i) \end{aligned} \quad (2)$$

where $i = 1, 2, \dots, 8$, represents the i th interface of contacted materials from center to edge in the coaxial TSV; R_i is the radius of the i th interface; P_i and P_{i+1} represent the materials on either side of the i th interface, respectively; u_r , u_z , and σ_{rz} are the displacement vector along r , z axis in cylindrical coordinate system, and shear stress, respectively.

3 Model verification

ANSYS simulation was performed to verify the analytical model. Cu and SiO₂ are selected as the TSV metal and dielectric materials. The physical constants used are: $\alpha_{Cu} = 18 \text{ ppm/}^\circ\text{C}$, $E_{Cu} = 110 \text{ GPa}$, and $\nu_{Cu} = 0.35$ for Cu, $\alpha_{SiO_2} = 0.6 \text{ ppm/}^\circ\text{C}$, $E_{SiO_2} = 72 \text{ GPa}$, and $\nu_{SiO_2} = 0.16$ for SiO₂, and $\alpha_{Si} = 2.3 \text{ ppm/}^\circ\text{C}$, $E_{Si} = 130 \text{ GPa}$, and $\nu_{Si} = 0.28$ for Si. Thermal load $\Delta T = -250^\circ\text{C}$.

Fig. 2 shows the thermal stress results got from analytical solution with ANSYS simulation. To decrease the discrepancy of the model from ANSYS simulation results, the analytic solutions are multiplied by the correction factor (CF=2.5). The average relative error of corrected analytical solution as compared to ANSYS simulation result is less than $\sim 2.5\%$, which proves the accuracy of the analytical model.

Fig. 2. Comparison of thermal stresses got from analytical solution with ANSYS simulation

4 Thermo-mechanical performance

Based on the analytical model proposed above, the thermo-mechanical performances on different coaxial TSV sizes are discussed in this section.

We tune the cylindrical metal diameter to be $3\mu\text{m}$, $4\mu\text{m}$, $5\mu\text{m}$ (baseline), $6\mu\text{m}$ to $7\mu\text{m}$. Thermal stress results are summarized Fig. 3. It is shown that the stress grows as the cylindrical metal diameter ramps up. The stress is decreased by 342MPa at the coaxial TSV edge as the cylindrical metal diameter varies from $7\mu\text{m}$ to $3\mu\text{m}$. Therefore, the equivalent area of coaxial TSV, defined as the area of TSV and the surrounding keep-out-zone, can be greatly decreased.

Fig. 3. Thermal stress vs. cylindrical metal diameter

Fig. 4 summarizes the influence of dielectric thicknesses on thermal stress. The dielectric thickness is varied from $1\mu\text{m}$, $2\mu\text{m}$, $3\mu\text{m}$ (baseline), $4\mu\text{m}$ to $5\mu\text{m}$. As shown in Fig. 4, the thicker the dielectric, the higher the stress. However, dielectric thickness has less influence than cylindrical metal diameter on the thermo-mechanical performance. The reason is that dielectric material (SiO_2) has less CTE mismatch with silicon than TSV metal (Cu).

Fig. 4. Thermal stress vs. dielectric thickness

The tubular metal thickness impact on the thermal stress state is also studied. Fig. 5 gives the results as tubular metal thickness is changed from $1\mu\text{m}$, $2\mu\text{m}$ (baseline), $3\mu\text{m}$, $4\mu\text{m}$ to $5\mu\text{m}$. It is found that, compared with the tubular metal thickness of $1\mu\text{m}$, the $5\mu\text{m}$ case enlarge the stress by 582MPa (245%) at the TSV edge. Tubular metal thickness has much greater influence on the thermo-mechanical performance than other parameters. This is because tubular metal is adjacent to substrate.

Fig. 5. Thermal stress vs. tubular metal thickness

We change TSV height from 10 μm , 30 μm , 50 μm (baseline), 70 μm to 90 μm , and the thermal stress results are shown in Fig. 6. It is found that the radial stress could hardly be affected by TSV height.

Fig. 6. Thermal stress vs. TSV height

5 Conclusion

Accurate analytical model for the thermal stress induced by Cu and SiO₂ filled coaxial TSV are presented and verified by ANSYS. It is shown that average relative error of stress is less than $\sim 2.5\%$. Based on the analytical model, performance impacts of various coaxial TSV configurations are evaluated. Results give the Cu and SiO₂ filled coaxial TSV design guide lines: 1) the smaller the sizes of metal parts, especially the outer metal shell, the better the thermo-mechanical performance; and 2) the dielectric size and the TSV height play unimportant roles on the thermal stress state.

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